Structural thermal Optical Performance (STOP) analysis in SWOT and WFIRST

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Contents

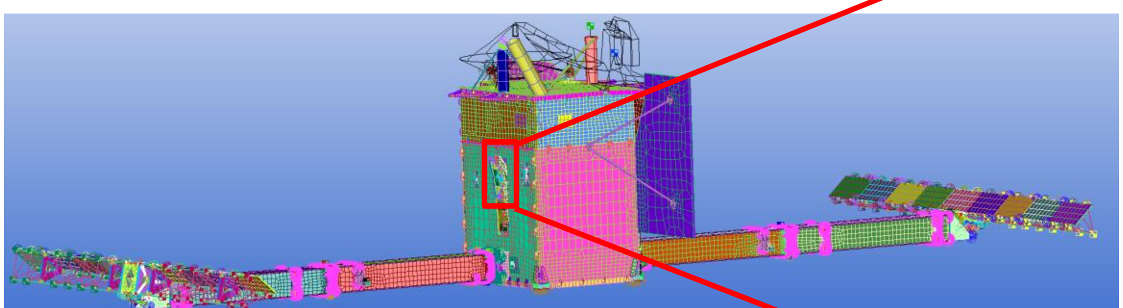
Introduction

- Thermal deformation is one of the major sources that can degrade the performance of a space telescope or antenna.
- Structural Thermal Optical Performance (STOP) analysis is the tool to assess the performance of a space instrument under thermal loads.
- STOP analysis includes
  - ✓ Thermal analysis
  - ✓ Structural (thermo-elastic) analysis
  - ✓ Optical analysis
- This talk addresses the STOP analysis from the standpoint of a structural analyst.

Structural Model

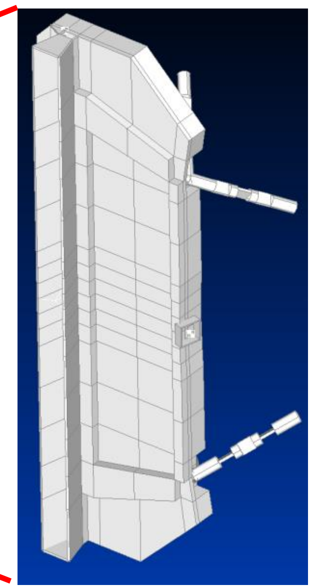
- Structural model for STOP analysis
  - ✓ Output request: displacements only. Requires relatively coarse mesh, compared to models used for stress analysis.
  - ✓ A lot of analysis to perform.
  - ✓ Try to minimize the size of the STOP model
  - ✓ Can be used for other analysis, i.e., modal analysis, jitter analysis, random vibe analysis

SWOT Instrument

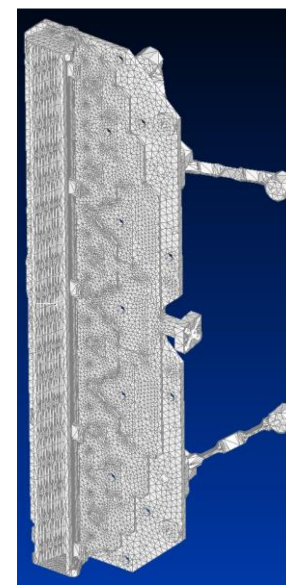


208487 nodes

Feed (from Faz Keyvanfar)



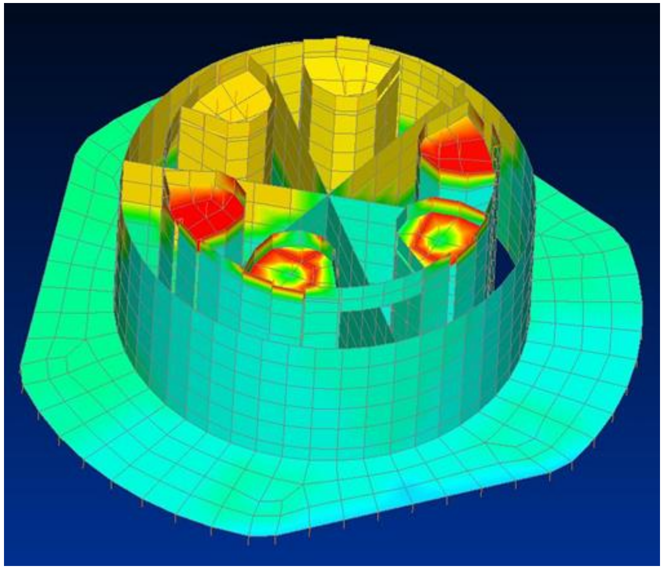
575 nodes



221279 nodes

Construction of Models

- Thermal model and structural model constructed based on the same CAD model
  - ✓ Mesh size may be different
  - ✓ Fidelity of components may be different
- Thermal model must include features important to structural analysis – not true vise versa.



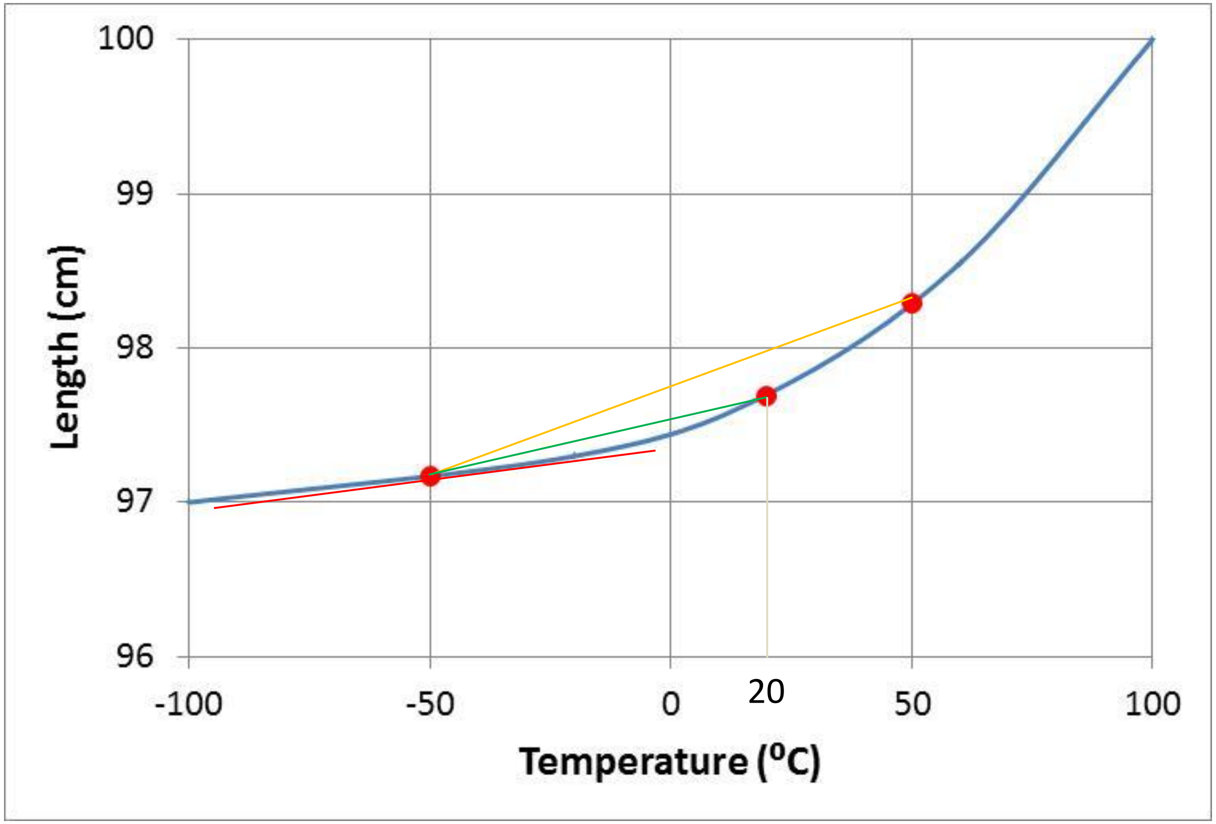
SWOT - Hexafoil

Temperature Dependent CTE

- Due to the requirement for high accuracy, temperature dependent CTE is used for calculating thermal loads.
- When using temperature dependent CTE, there are some limitations on the structural model:
  - ✓ No RBE1 or RBE2 elements on load path – although Rigid Body Elements can be assigned CTE, the CTE is constant. Can be replaced by stiff PBEAM elements
  - ✓ No PBAR elements – PBAR does not accept temperature dependent material properties. Can be replaced by PBEAM elements
  - ✓ No composite laminate elements – PCOMP does not accept temperature dependent material properties. Can be replaced by PSHELL elements.
  - ✓ CROD, CBEAM, CGAP, CQUAD4, CQUAD8, CTRIA3, CTRIA6, CHEXA, and CTETRA elements can be used.
- Control cards for analysis with temperature dependent CTE
  - ✓ Use TEMP(BOTH) only - TREF of the MAT must be defined correctly
  - ✓ If TEMP(INIT) and TEMP(LOAD) are used, Nastran picks the CTE at the initial temperature (wrong).
  - ✓ If only TEMP(LOAD) is used, Nastran picks the constant CTE assigned by the MAT cards (wrong).

Temperature Dependent CTE (cont.)

- Nastran takes Secant CTE
  - ✓ Construct the Secant CTE table based on the reference temperature



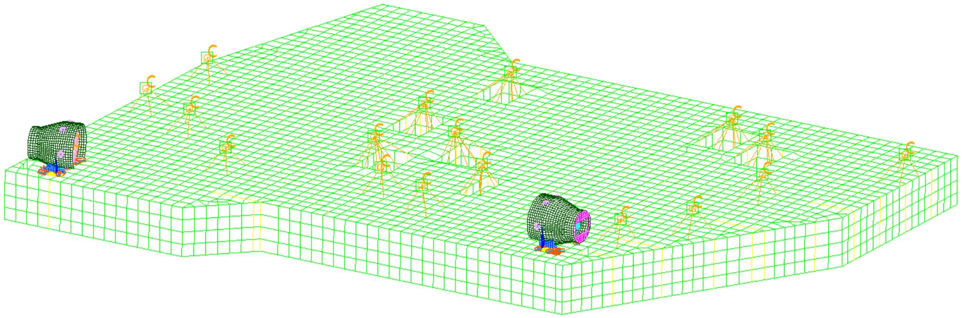
CTE at -50 °C

- Tangential
- Secant based on 20 °C
- Secant based on 50 °C

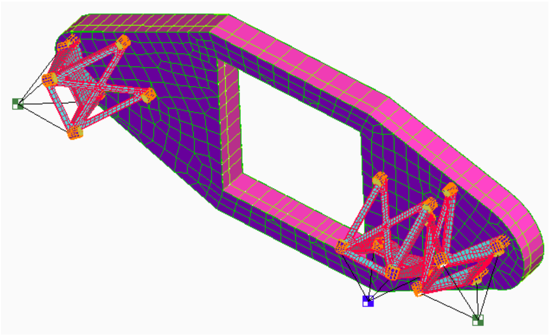
CTE for RBE3

- RBE3's can be used to spread load and mass for devices such as electronic boxes, etc.
- Whether CTE is assigned to a RBE3 depends on the purpose.
  - ✓ Example 1: for optics w/o detailed design on WFIRST Coronagraph Bench, CTE of supporting structure is assigned to the RBE3's
  - ✓ Example 2: at the I/F of star trackers and supporting brackets where RBE3's are used to calculate the average of I/F translations and rotations, no CTE is assigned

WFIRST Coronagraph Bench



SWOT Star Tracker



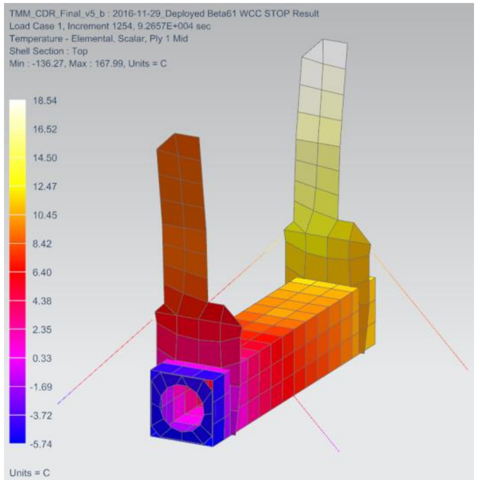
Model Check

- Nastran Groundcheck
  - ✓ Perform grounding check analysis on the stiffness matrix to expose unintentional constraints by moving the model rigidly.
- Maximum Diagonal Ratio < 1E+7
  - ✓ An error indicates unconstrained mechanism, bad connection of different types of elements, etc.
- NASTRAN Epsilon < 1E-8
  - ✓ A measure of numerical accuracy and round off error
  - ✓ A ratio of work done by residual forces to the work done by the applied forces $\varepsilon = \frac{u^T \{P - Ku\}}{u^T \{P\}}$
- Free-Free Modal Checks
  - ✓ In unconstrained condition, the model should have six rigid body modes with frequencies below 0.005 Hz
  - ✓ The ratio of the lowest elastic mode frequency and the highest rigid body mode frequency should be greater than 10

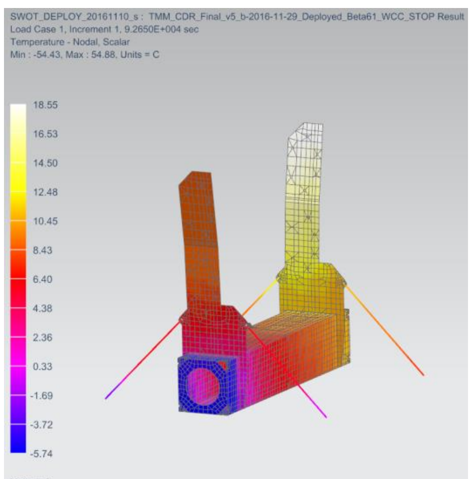
Temperature Loading Checks

- Loading temperature equals reference temperature ($\Delta T = 0$)
  - ✓ Forces and moments less than 0.01 N and 0.01 N-m
  - ✓ Displacements less than 1E-12 m
  - ✓ Make sure TREF field in MAT and PCOMP cards are set correctly
- Temperature perturbation about nominal temperature
  - ✓ Assign the same CTE to all materials
  - ✓ Kinematically constrain the model
  - ✓ The worst-case difference in magnitude between the model and analytic prediction at any optically significant point should be less than 1e-9 meters

Temperature Mapping



Thermal model



Structural model

SWOT – Metering Structure

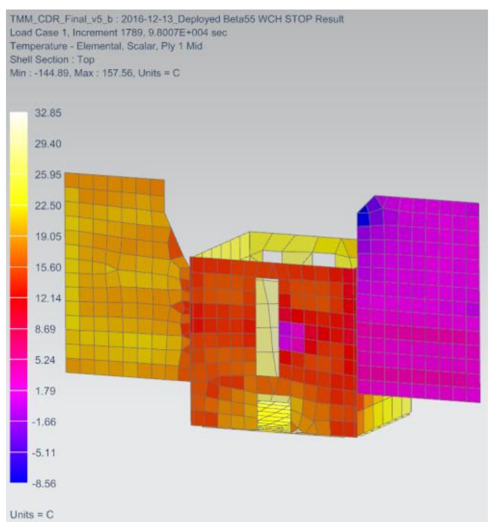
- Temperature mapping is required because the thermal model and the structural model are different.
  - ✓ Due to the nature of thermal analysis (lots of iterations), thermal model can't afford the same fidelity and fine mesh as structural model can.
- Temperature distribution across the system is derived through thermal analysis using thermal model.
- Thermal distortion is calculated through thermo-elastic analysis using structural model.
  - ✓ Temperature distribution from thermal model must be mapped onto the structural model.

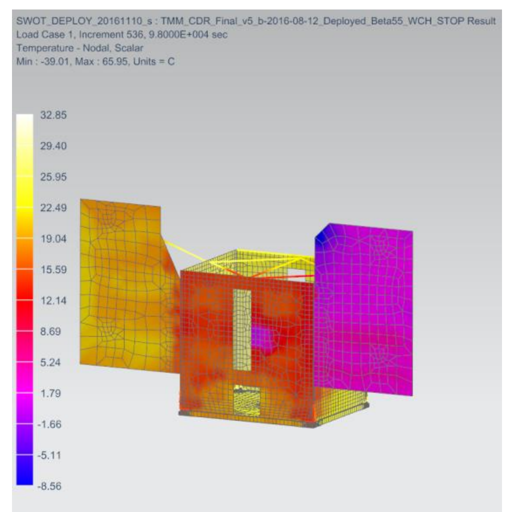
Temperature Mapping

Quality Check

- Make sure all the structural nodes are mapped. If not:
  - ✓ Increase tolerance – increase the distance the tool is allowed to search for thermal nodes.
  - ✓ Run a steady state thermal analysis using the structural model, with the mapped temperature as fixed Boundary condition.
- Compare contour plot ranges and gradients between thermal and structural models

Thermal model





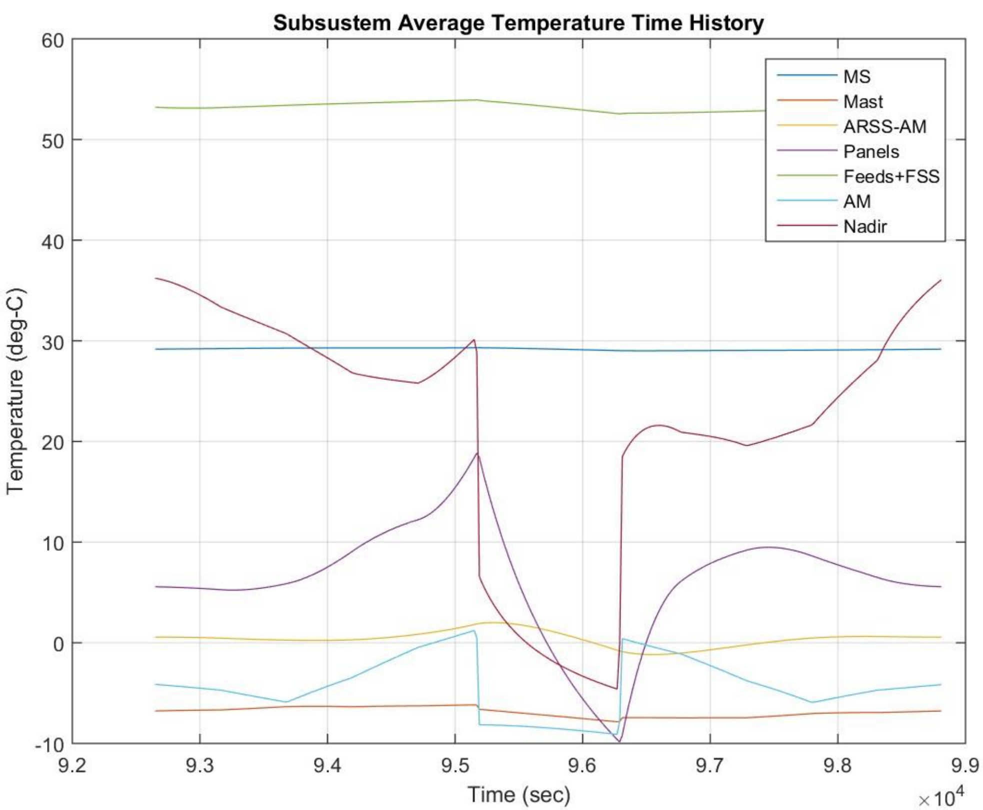
Structural model

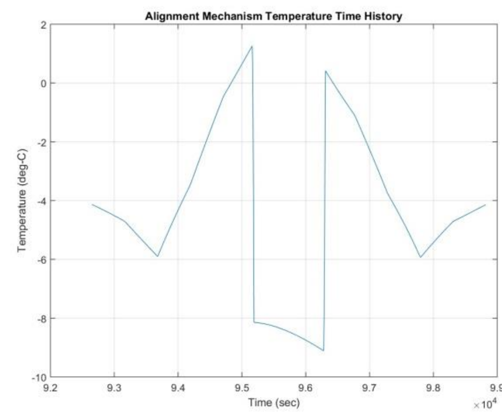
SWOT – KaRIn Module

Temperature Mapping
Quality Check (cont.)

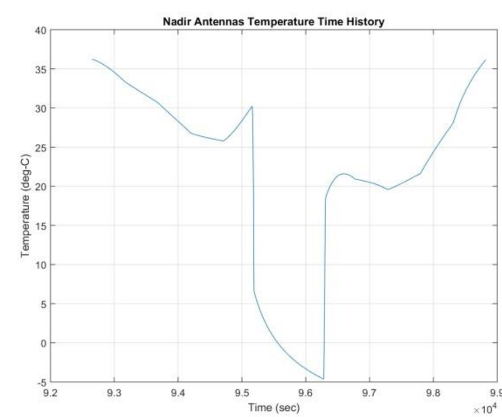
Two MatLab scripts were written to monitor the temperature time history.

- Plot time histories of average temperature of subsystems.
- Check the time history of each and every node. Signal the time steps and nodes that show drastic temperature change between 2 consecutive steps.





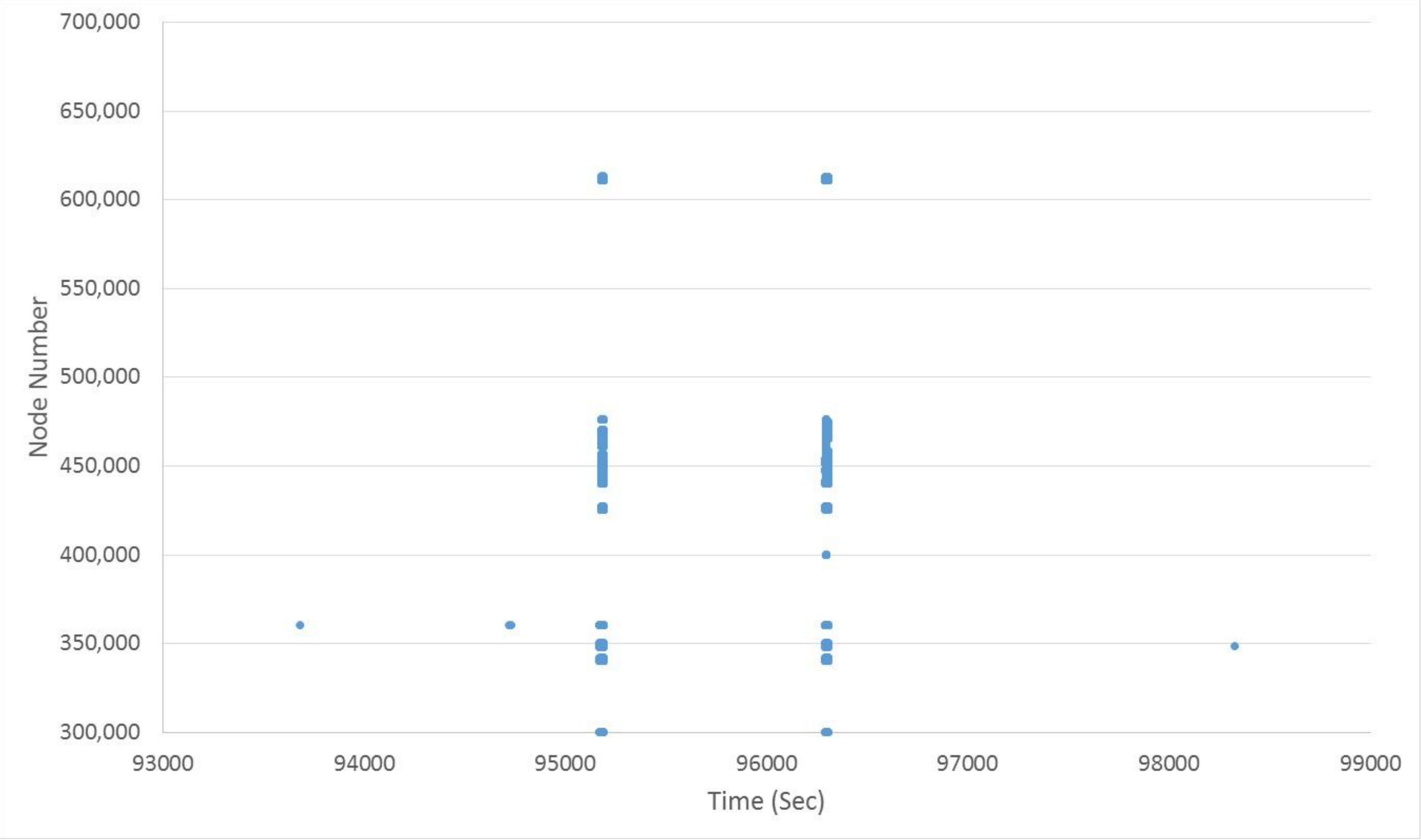
AM



Nadir

Temperature Mapping
Quality Check (cont.)

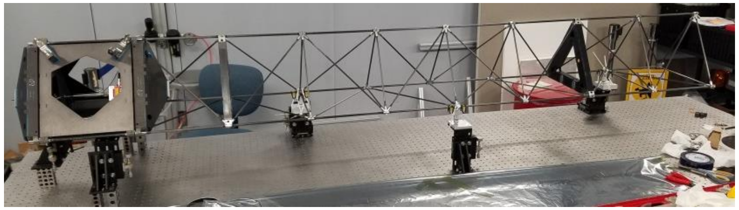
The figure indicates which subsystem (nodes of the same subsystem are grouped together) and time steps may have problems.



Empirical Modeling

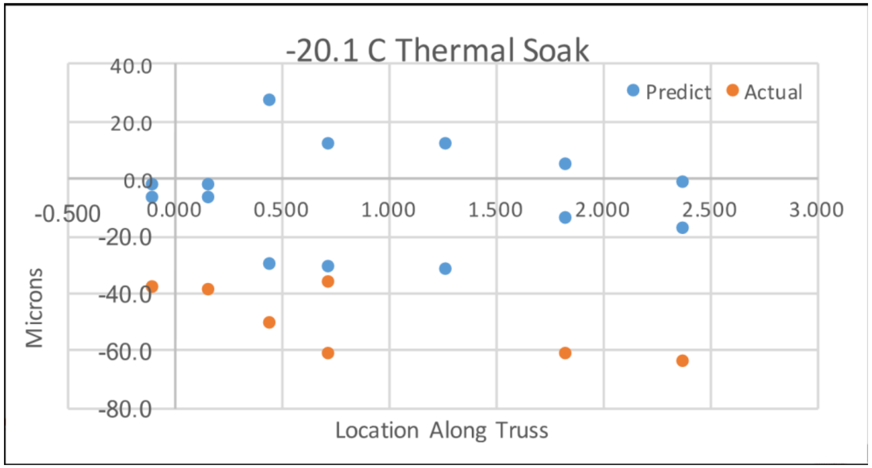
SWOT IRA

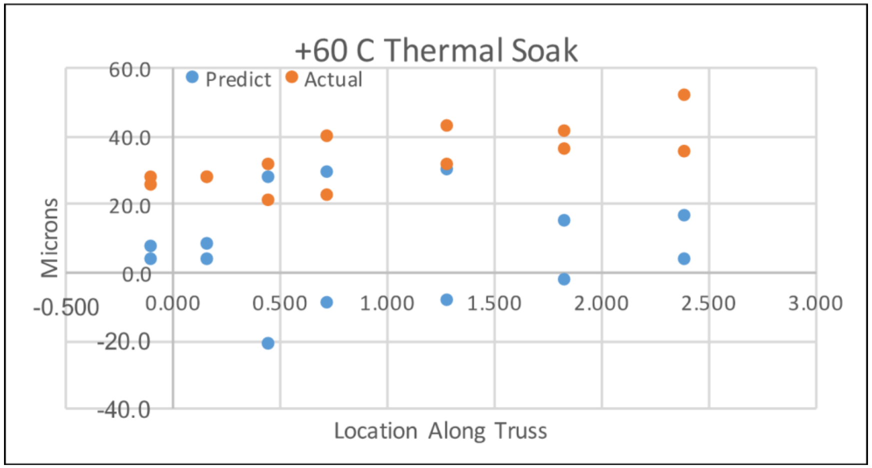
EM Truss



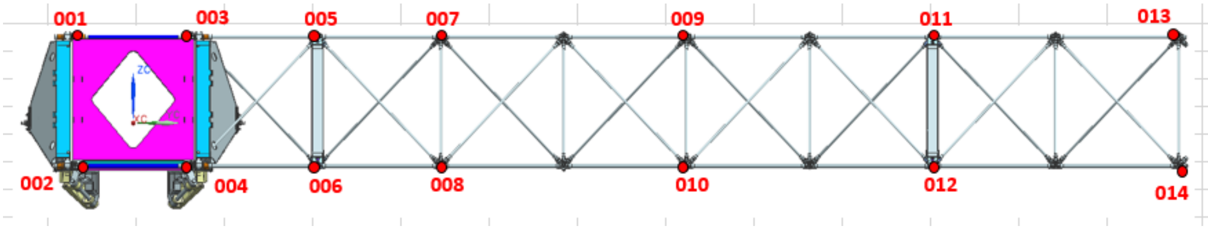
Background

- Thermal test performed on EM of IRA
  - ✓ 4x thermal cases: -20 C, -10 C, +60 C, +92 C
- Correlation between prediction and test is not good.





Measurement Locations

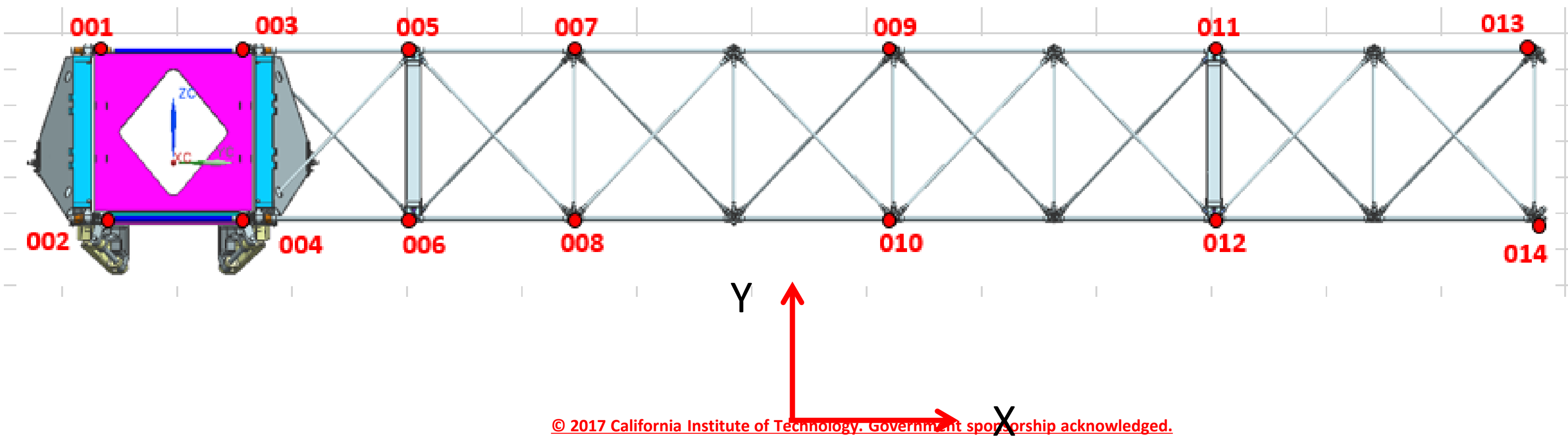


Simplification of the Problem

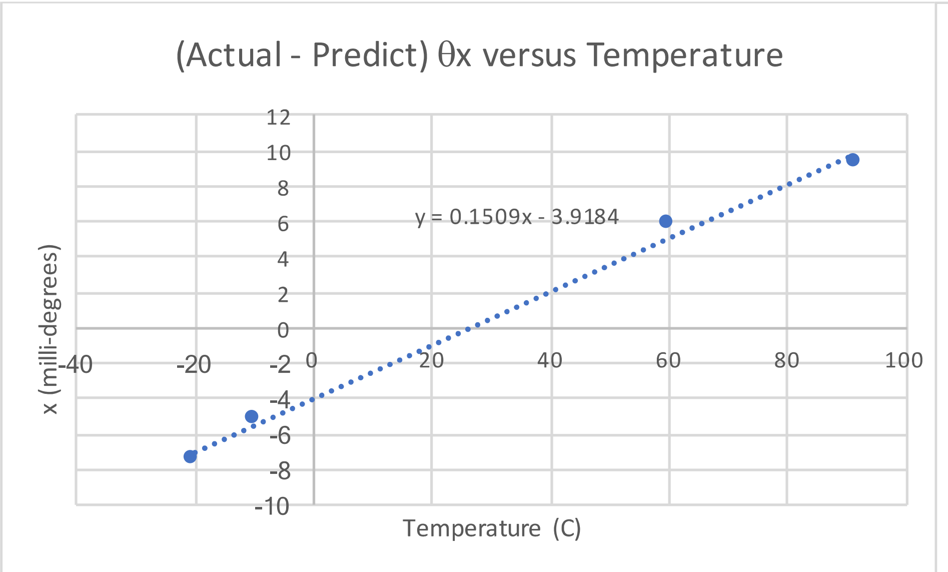
(methodology conceived by Eric Slimko)

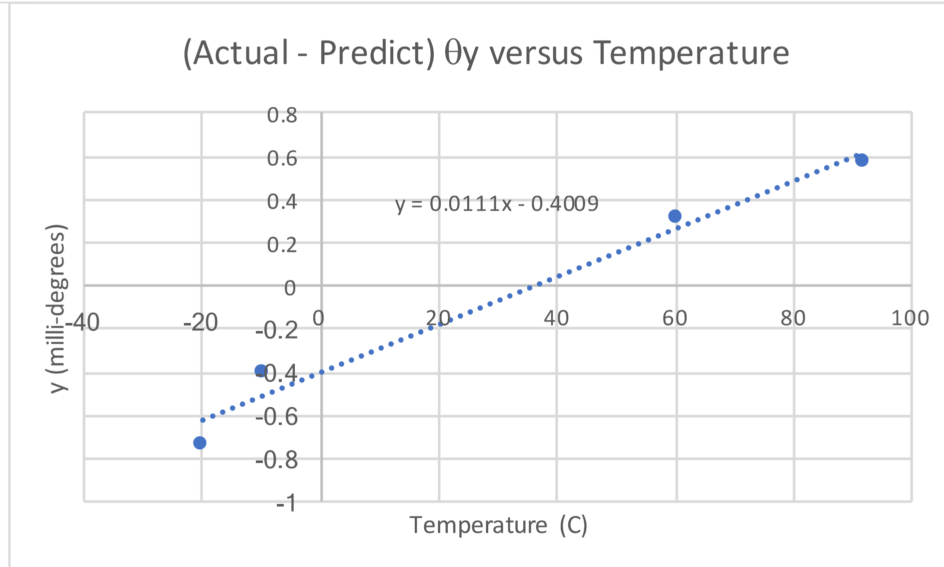
- The thermoelastic test data was significantly different than pre-test predictions in a non-obvious pattern.
- The KaRIn instrument is sensitive primarily to the orientation and location of the best-fit plane to the reflectarray.
- Calculate Best-fit plane for both prediction and test measurements and compare.

Measurement Locations



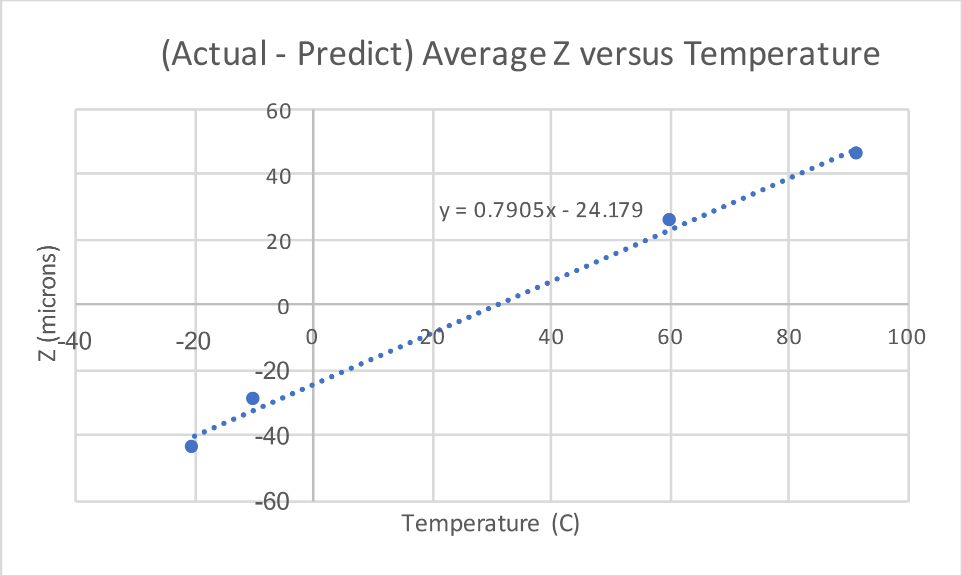
Angular Results





The error in X and Y angles between the actual and the prediction is linear in temperature. This suggest there is a simple correction to a single CTE across the temperature range will correct the prediction. θx is off by 0.151 milli-degree/C and θy is off by 0.011 milli-degree/C.

Displacement Results



The error in average Z displacement between the measurement and the prediction is linear in temperature by 0.79 microns/C. This suggests a simple correction to a single CTE will resolve the issue.

Best-Fit Plane Conclusion

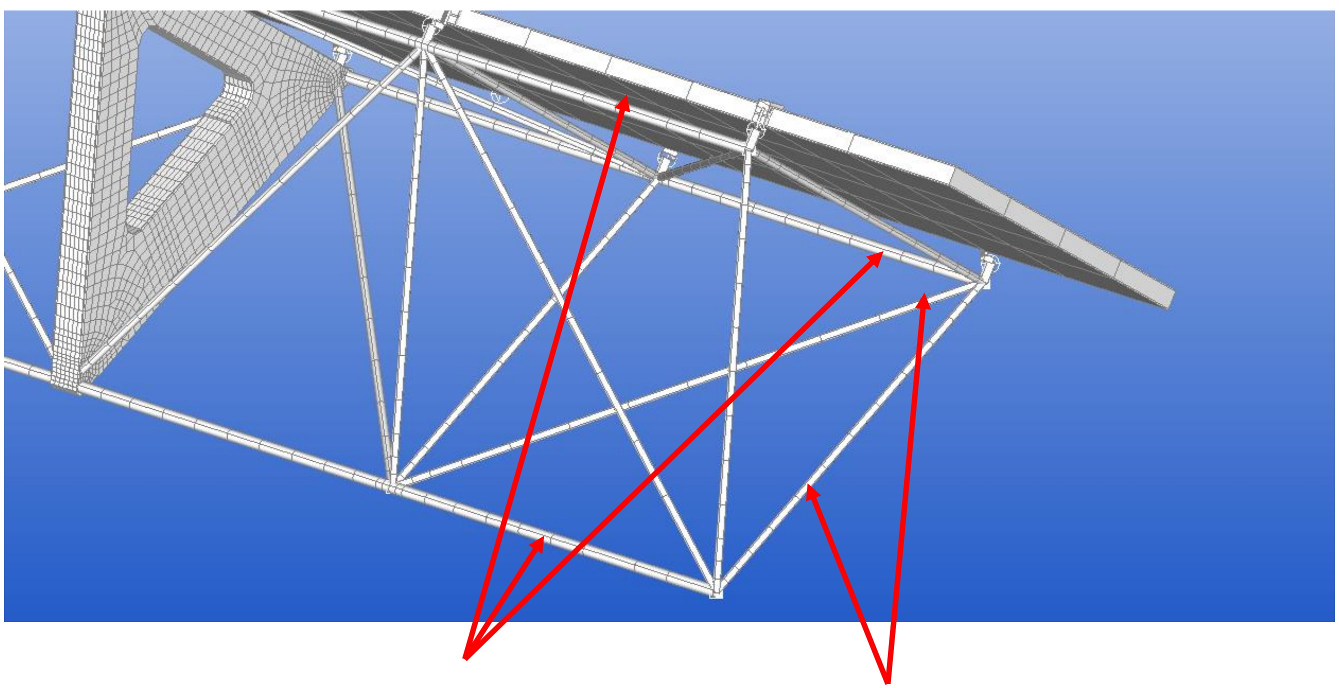
- Given that the primary parameters of concern at the system level are the angular orientation and displacement of the best-fit plane to the reflectarray, this analysis suggests the difference between test measurement data and the test prediction may be resolved with straightforward changes to a very limited set of CTE parameters

- In the near term, we'd like to use this simplified strategy to quickly adjust the existing model to envelope the test data such that we can use this "quasi-empirical" model in system level analysis

- In the longer term, this strategy may provide guidance for understanding what the correlation issue actually is

Sensitivity Study of IRA Truss

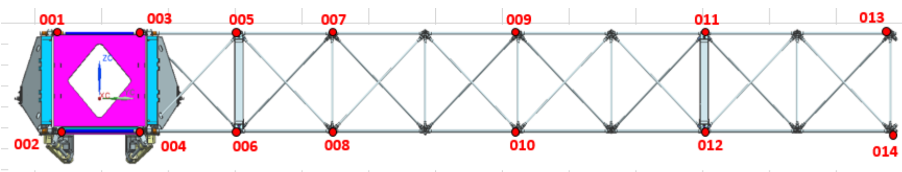
- CDR STOP FEM model used for the study
- Thermal soak analysis done at -50 ^{o}C (reference = 20 ^{o}C)
- CTE of longeron or diagonal truss members changed by 1 ppm/ ^{o}C)
- Displacement and rotation of reflector panels calculated



Longeron Diagonal

Sensitivity Study of IRA Truss (cont.)

Measurement Locations



Difference between measurement and prediction

Z-Disp (micron/C)	X-rotation (milli-deg/C)	Y-rotation (milli-deg/C)
0.79	0.151	0.011

Sensitivity for +1 ppm/ ^{0}C change of diagonal CTE

Z-Disp (micron/C)	X-rotation (milli-deg/C)	Y-rotation (milli-deg/C)
0.0409	0.202	0.016

Z-Disp (micron/C)	X-rotation (milli-deg/C)	Y-rotation (milli-deg/C)
0.0409	0.202	-0.016